N91-10872

Progress in Computing Nozzle/Plume Flow Fields

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Abstract

The long-term goal of this work is to develop the capability to predict chemically-reacting, multi-stream nozzle and plume flow fields. Two basic Navier-Stokes solvers, including the widely used F-3D code, are upgraded to include several upwind difference schemes and portable chemistry packages. Current computational capabilities for solving eqilibrium single-stream and multi-stream, frozen gas and finite rate chemistry problems are described. A variety of complex nozzle and plume flows have been computed. Solutions presented herein include axisymmetric plume flow for ideal and equilibrium air, 3-D NASP nozzle/afterbody flow, and an internal nozzle calculation comparing various finite-rate chemistry packages.

Motivations, Objective, and Applications

Motivations

- Flow in nozzle and propulsive plume strongly influence performance of hypersonic vehicles.
- Ground-based facilities can not fully simulate these flow fields.
- Validated, accurate and efficient flow codes are needed to design integrated propulsion systems of hypersonic vehicles.

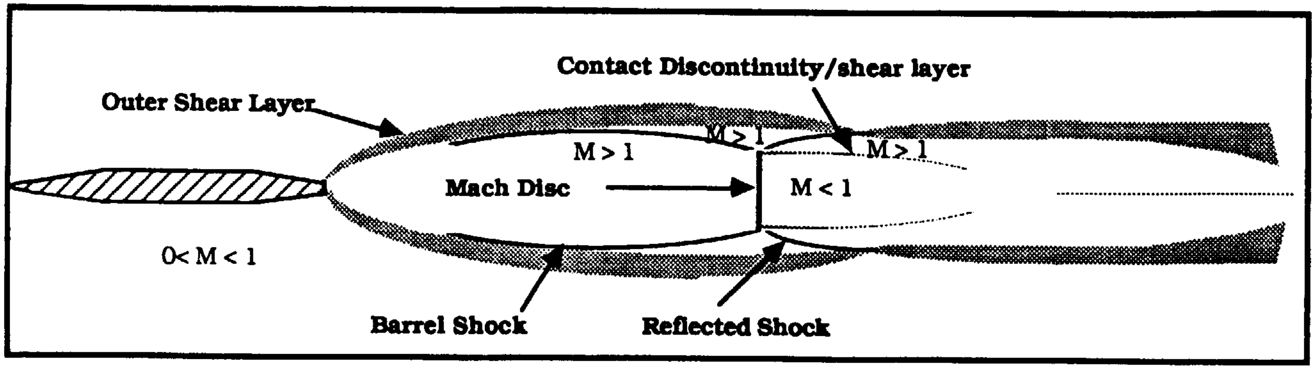
Objective

- Develop computational ability to predict chemically reacting, multi-stream, nozzle/plume flow fields.

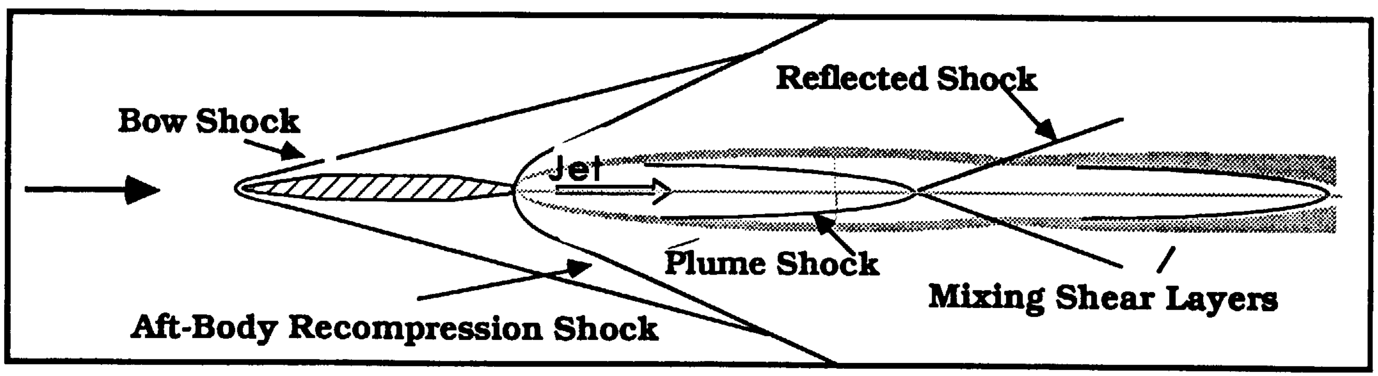
Applications

- NASP, Space Shuttle, general plume flows and signatures

SCHEMATIC OF AXISYMMETRIC PLUME FLOWS



Plume Flow in Subsonic External Stream



Plume Flow in Supersonic External Stream

Nozzle/Plume Flow Solvers

Difference Scheme	2-D Axisym. Eqns. Flux-Split in 2-D	3-D Eqns. Flux-Split in 1-D Central Diff. in 2-D	3-D Eqns. Roe's upwind averaging in 3-D
Implicit Soln. Algorithm	Beam & Warming in "delta form"	Two-Factor Flux-Split	LDU-ADI
Viscous Terms	in 1-D	in 1-D	in 3-D
Chemistry	Ideal Gas Equil. single-stream Equil. multi-stream Frozen	Ideal Gas Finite-Rate	Ideal Gas Equil. single-stream
Calibration	Ideal Gas: Mach disk location for jet plumes Equil. 1-stream: Shock standoff dist., and shape and species distribution for blunt body flow.	Ideal Gas: Numerous flows including Space Shuttle, Mach No., pressure and Mach disk location for plumes Finite-Rate: H_2 -air species distribution for axsymm. nozzle.	Ideal Gas: Numerous flows including Space Shuttle, Mach No., pressure and Mach disk location for plumes, plume structure in quiescent freestream

Nozzle/Plume Flow Solvers (cont.)

- All calculations performed for laminar flow
- Adaptive grid routine used for all 2-D cases
  (3-D adaptive grid routine recently completed)
- 3-D code can handle multiple, patched-grid regions and generalized specification of boundary conditions

Equilibrium and Frozen Gas Chemistry

<u>Constant Elemental Composition (i.e., single-stream)</u>

- Uniform gas throughout flow field

  Equilibrium Gas
  - table look-up, curve fits
  - relatively fast
  - must be pre-calculated

<u>Variable Elemental Composition (i.e., multi-stream)</u>

- Solution of species partial density equations allows for convection, diffusion and mixing of multiple streams

  Equilibrium Gas
  - Gordon-McBride free energy minimization
  - arbitrary gas mixtures

  Frozen Chemistry
  - No reactions

Finite Rate Chemistry

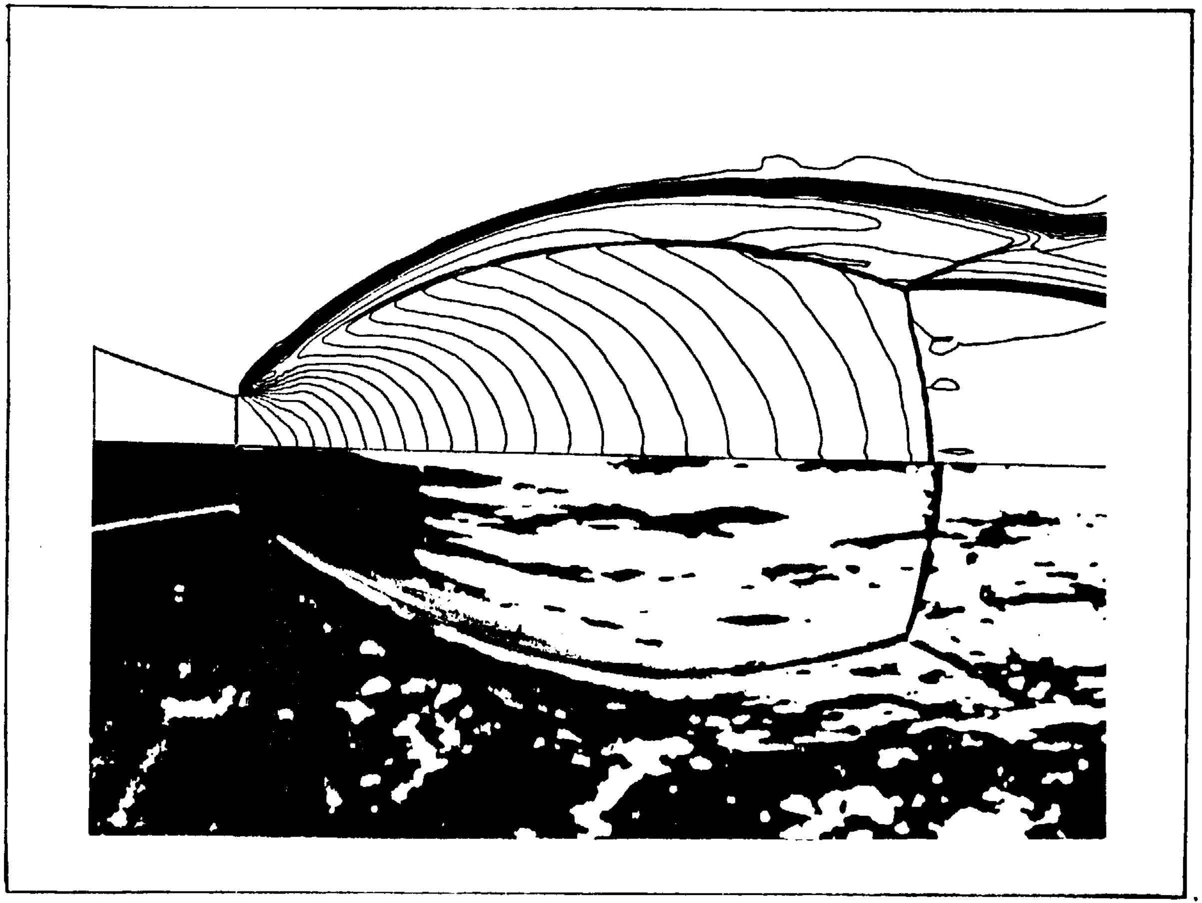
- H_2 - air chemistry currently being used
  - JANNAF plume model (Dash and Pergament, 1980)
  - 7 Species: H, H_2, H_2O, O, OH, O_2, N_2
  - 8 Reactions
- Specific heats from curve fits (Gordon and McBride data)
- Binary diffusion
  - Fick's Law with $D_{i,j}$ given by Reid, et.al., 1977)
- Non-catalytic wall
- Chemistry Coupling
  - Fully-Coupled
    - Invert large matrix of order $5 + (N_{species} - 1)$ per node
  - Loosely-Coupled
    - Locally constant $\bar{\gamma}$
    - P not affected by species concentration variations
    - Invert two smaller matrices of order 5 and $N_{species} - 1$ per node.

Types of Nozzle/Plume Flows Computed

Cases	Main complexity is due to: Fluid Dyn. Features	Body Geom.	Flow Chem.	References
I. Axisymmetric Single-Nozzle Plume				
A. Not including afterbody				
Ideal gas, sub. freestream	X			AIAA 89-0129
Ideal gas, sup. freestream	X			AIAA 88-3158
B. Including afterbody				
Ideal Gas	X	X		AIAA 88-2636
Equil. single-stream	X	X	X	AIAA 88-2636
Equil. multi-stream	X	X	X	in preparation
Frozen	X	X	X	in preparation
II. 3-D Multiple-Nozzle Plume				
A. Not including afterbody	X			AIAA 88-3158
B. Including afterbody	X	X		AIAA 89-0129
III. Hypersonic Nozzle/Afterbody				
A. 2-D Geometry				
Subsonic freestream	X			AIAA 89-0446
Supersonic freestream	X			AIAA 89-0446
B. 3-D Geometry				
Plume region alone	X	X		AIAA 89-0446
Complete geometry	X	X		AIAA 89-0446
IV. Internal Nozzle, finite rate chem.			X	in preparation

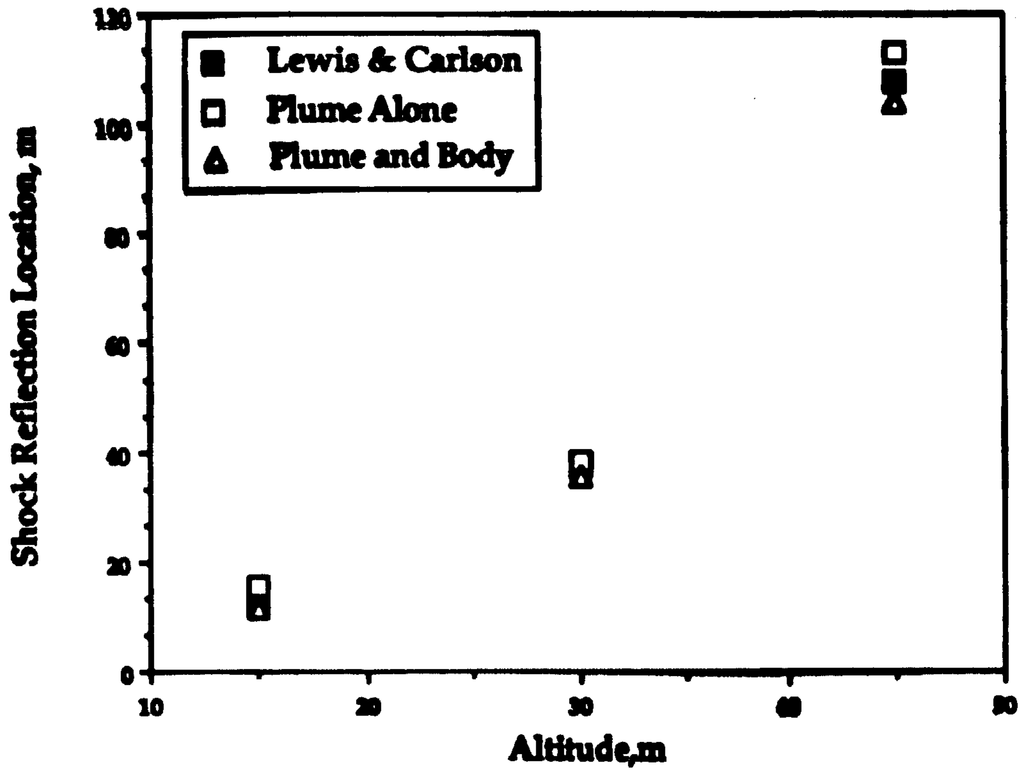
Axisymmetric Plume Flow in Quiscent Air
Pj/Pinf = 21.9 - Mj = 1.5

Upper Half - Computed Mach Contours with Adapted Grid

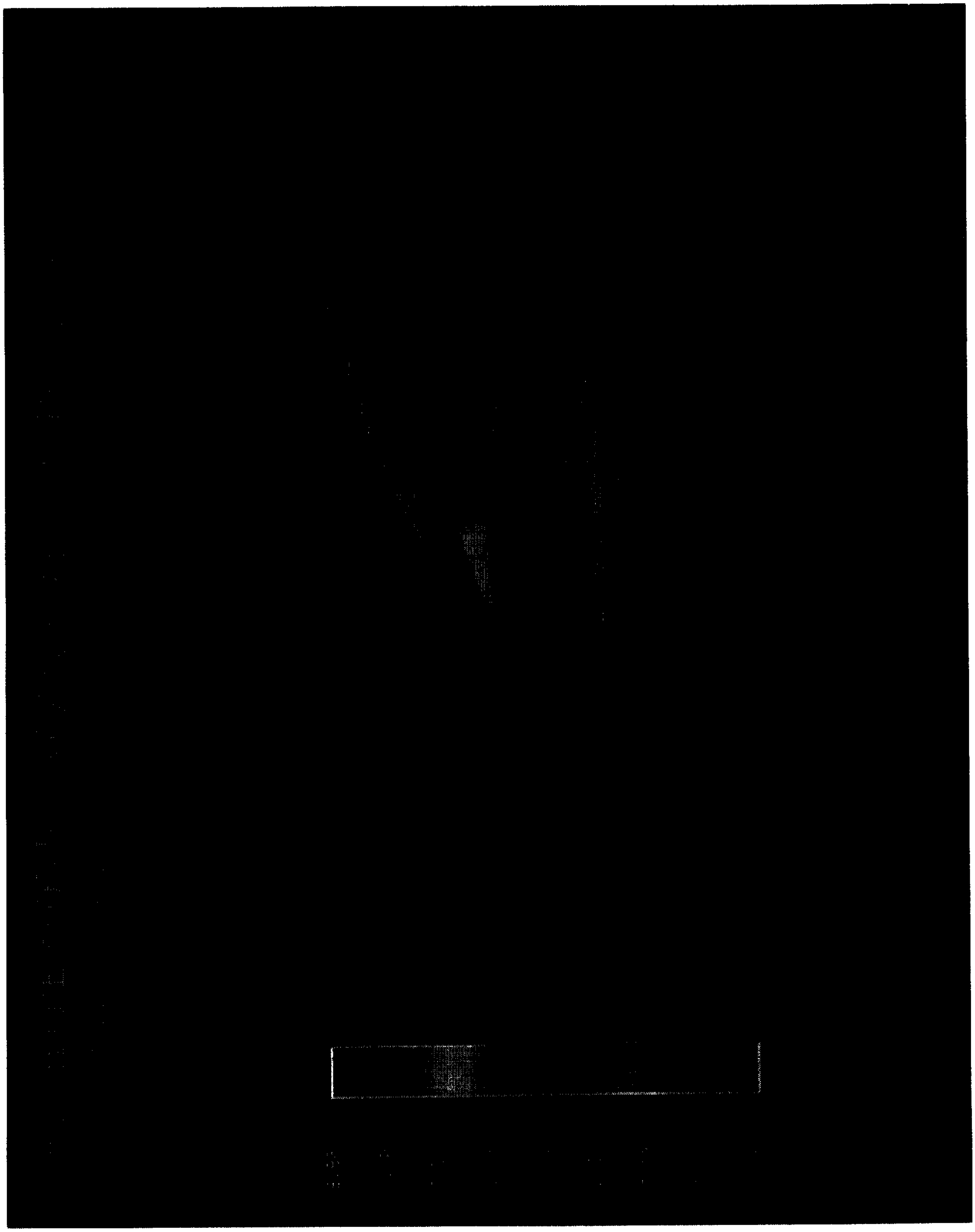


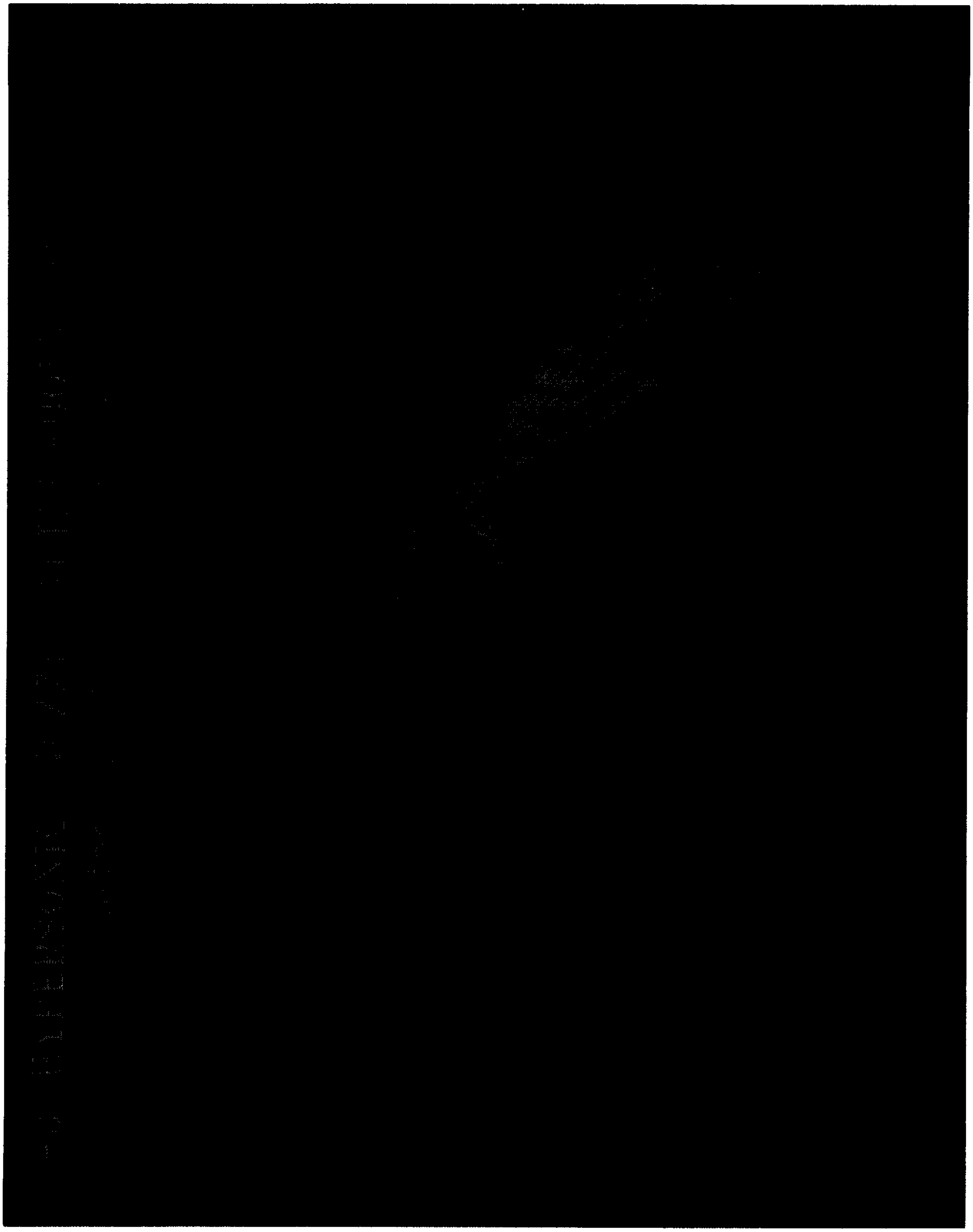
Lower Half - Experimetnal Shadowgraph - (NASA TR R 6)

Axisymmetric Plume Solutions

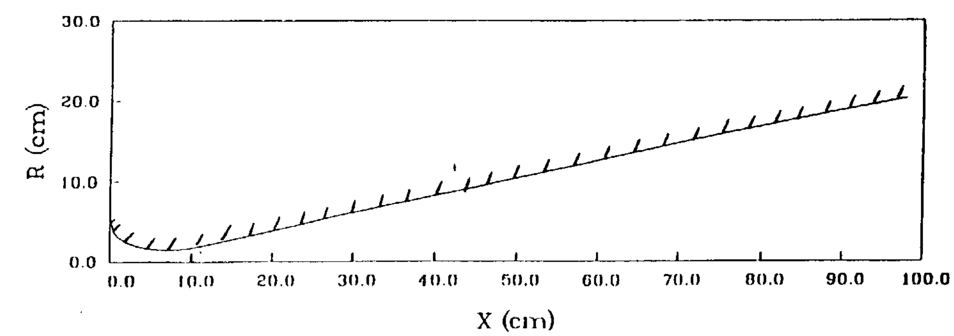


Comparison of Shock Reflection Location vs Altitude

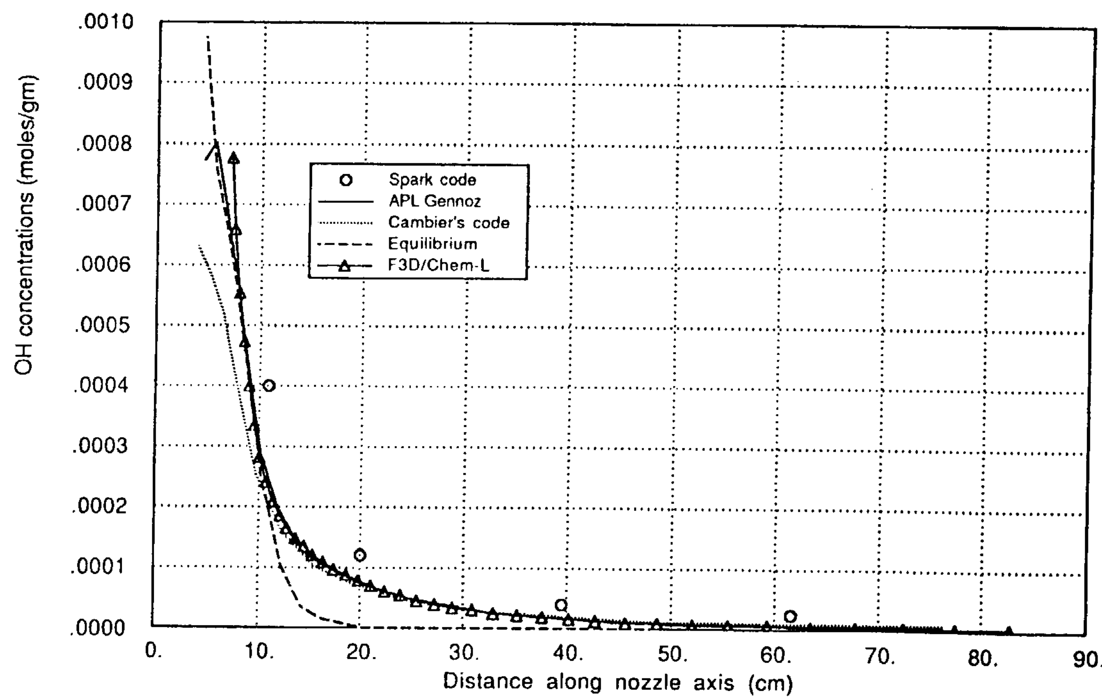




NOZZLE GEOMETRY



OH CONCENTRATIONS VERSUS DISTANCE ALONG NOZZLE AXIS



Concluding Remarks

- A variety of nozzle/plume flows have been successfully computed.
  - Complex flow structures and geometries have been studied
  - Good agreement with experimental and other computed results has been found for plume structure and Mach disk location.
- Equilibrium single-stream, equil. multi-stream, finite rate, and frozen chemistry packages have been incorporated.
- Turbulence modeling for complex plume flows is currently being studied
- 3-D code will be validated against hypersonic nozzle/afterbody experimental data
- Significant progress has been made toward goal of a single code capable of solving complex chemically reacting nozzle/plume flow fields.